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COSMIC RAY COMPOSITION AND APPLICATIONS OF NUCLEAR EMULSION TECHNIQUE

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NUCLEAR EMULSION TECHNIQUE

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This thesis concerns three different experiments with the common feature that nuclear emulsion is used for particle track registration. Papers I and II treat the charge composition of nuclei in the cosmic radiation in the charge interval $14 \leq Z \leq 28$. Paper III is a study of the isotopic composition of cosmic ray iron with a combined plastic-emulsion detector. Papers IV and V treat measurement technique and handling of nuclear emulsion.

I. Composition of low energy cosmic radiation from silicon to nickel.

Published in Astrophysics and Space Science, 21, 211 (1973)
(In collaboration with S. Behrnetz, S. Lindstam and K. Kristiansson).

II. Composition of medium energy cosmic rays from silicon to nickel measured with nuclear emulsion.

Published in Astronomy and Astrophysics, 52 327 (1976).
(In collaboration with S. Behrnetz, S. Lindstam and K. Kristiansson).

III. Galactic cosmic ray iron composition.

Published as an internal report LUIP 8003, LUNFD6/(NFFK-8003)1-16 (1980) and registered as an abstract in International Nuclear Information System (INIS). Also submitted to Astronomy and Astrophysics.
(In collaboration with R. Scherzer, W. Enge, R. Beaujean, S. Hertzman and K. Kristiansson).

IV. On the production of thick pellicles of Kodak NTB-3 nuclear track emulsion. Published as in internal report LUIP 8002, LUNFD6/(NFFK-8002)1-7(1980) and registered as an abstract in International Nuclear Information System (INIS). Also submitted to Nuclear Instruments and Methods.
(In collaboration with G. Claesson and G. Ingelman).

V. Detection of short-lived particles in nuclear emulsion.

Published in Nuclear Instruments and Methods, 165, 1 (1979).
(In collaboration with B. Andersson, G. Claesson, G. Ingelman and I. Otterlund).

The space between the stars and the galaxies is filled with "radiations" of different kinds. Cosmic electromagnetic radiation has been detected in a broad spectrum from long wave radio radiation to hard γ -rays. Of special interest is the 3⁰K blackbody radiation which is considered to be a remnant of a Big Bang which created the universe we see today. It is also believed that the Big Bang created a background of neutrino radiation of the same temperature and if recent experimental results on the mass of the neutrinos are correct, the neutrinos may even dominate the mass of the universe.

The term "cosmic radiation" is however, usually restricted to another component of radiation or to the high energy particles which traverse the space. We now know that the major part of the cosmic radiation is atomic nuclei accelerated to high energies. Since its discovery about 7 decades ago the main problem with cosmic rays has been to find the origin of the radiation. Most of the particles in the cosmic radiation are now considered to be of galactic origin and they are known to be more or less confined to our galaxy by the interstellar magnetic fields. An important clue to the origin is the composition of the radiation in different energy regions. In a first view the composition is quite similar to "normal" cosmic matter. Hydrogen dominates, the helium fraction is about 10% of the particles and the heavier elements constitute less than 1 per cent. A closer study will however reveal some interesting differences. It has for long been known that the elements Li, Be and B are overabundant in the radiation. This is also the case for Sc, Ti, V, Cr and Mn. These elements have predominantly been produced in interstellar space when heavier nuclei were split up in collisions with interstellar matter. With assumptions on the initial abundances and knowledge of the relevant interaction cross sections it is possible to calculate the amount of matter traversed by the radiation. If we know the density of the interstellar matter we can also estimate the age of the radiation. The abundances in the radiation observed at the solar system can be corrected for the changes produced by interstellar spallation reactions by a proper extrapolation in order to get the source abundances. When the source abundances,

calculated in this way, are compared with the solar system abundances there still remains differences for a number of elements. This has led to a recent interest in charge-dependent selection effects, which could alter the composition of the matter prior to the acceleration to cosmic ray energies.

In the last few decades our knowledge of the production of the heavy elements has improved considerably. According to the current view on nucleosynthesis, most of the helium in the universe was produced in the Big Bang, and the elements with $Z \geq 6$ were synthesized later in heavy stars, and subsequently distributed in the interstellar medium by different processes. Some of the heavy elements, notably those in the iron peak, are believed to be produced in supernova explosions. An interesting result of model calculations, of explosive nuclear synthesis is, that the distribution of nuclei in the iron peak depends on the neutron excess in the particular layer in the exploding star, where the nuclei are synthesized. The neutron excess is defined as $\eta = (N_n - N_p)/(N_n + N_p)$ where N_n and N_p are the fractions of neutrons and protons respectively, free or bound in nuclei. This quantity is probably different for the individual supernovae. An important parameter seems to be the mass of the exploding star. Hence the different supernovae may introduce their individual signatures in their cosmic vicinity. If the nuclei in the cosmic radiation originate from such regions we would be able to find the traces of these signatures in the radiation we observe in the solar system.

Several different detection techniques have been applied in the study of the nuclear and isotopic composition of the cosmic radiation. Counter telescopes of various designs have been flown both with balloons and in satellites. Passive track detectors, notably emulsion and plastic detectors, have also been used. Each technique has its advantages and its problems. One important problem with counter telescopes is the difficulty to reveal nuclear interactions in the detectors. Failure to do this may lead to an erroneous identification of the particles. In nuclear emulsion even the loss of a single charge unit is easily detected. Passive track detectors have however one

obvious drawback, the analysis is time-consuming and it is therefore difficult to obtain good statistical accuracy.

Paper I presents a measurement of the charge composition of the cosmic radiation in the charge interval $14 < Z < 28$. The particles were registered with a stack of nuclear emulsion sheets exposed in a balloon flight over northern Canada in 1967. A high geomagnetic latitude was chosen for the exposure in order to allow particles of fairly low energy to reach the stack. The emulsion was scanned for heavy stopping particles and those with $Z > 14$ (156 in number) were selected for a closer study. The charge measurements were made with a photometric technique. The photometric track width is a function of the charge, mass and the residual range of the particle, but since the mass dependence is very slight, it has essentially been ignored in this investigation. Some corrections were applied to the raw data in order to compensate for various emulsion effects.

A special attention is paid to the abundance ratio S/Si. This ratio is not changed very much by spallation in the interstellar space or the atmosphere. The observed ratio should therefore be approximately equal to the ratio at the source. There is evidence for a real difference between the S/Si ratio in the cosmic rays and solar system ratio. This may indicate that there is a charge dependent selection mechanism working at the source.

In paper II material from two additional emulsion stacks exposed in 1970 has been added to the data presented in paper I making the total number of particles 276. The improved statistics motivated a more elaborate extrapolation of the abundances to the top of the atmosphere. Six different investigations of the abundances of the $14 < X < 28$ elements are compared. There are some notable discrepancies between the results, probably caused by charge dependent selection criteria, difficulties in charge separation and interactions in the detectors. The observed abundances of the elements Sc-Mn, which mostly are spallation products of iron, can be produced if a beam of pure

iron pass through 2.0 g cm^{-2} of hydrogen. In an exponential path length distribution model ($\exp(-x/\Lambda)$) a value of $\Lambda = 4.1 \text{ g cm}^{-2}$ fits the data. A comparison with the other experiments indicates that there may be an energy dependence for the abundance ratio (Sc-Mn)/Fe. The interpretation of this effect is not clear, but it may put a restriction on models for the propagation of the cosmic rays in the interstellar space. Several authors have argued that it is more realistic to consider models with more than one source of cosmic rays rather than a single one. One idea is to postulate an old source from which the radiation has passed through a large amount of matter and a new source from which the particles are virtually unaffected by interstellar spallation. The abundance of the $21 < Z < 25$ elements found in this investigation has been used to calculate the relative importance of the two sources in a two-component model proposed by Lundgaard, Rasmussen and Peters. A 40% contribution of the new source is found which is difficult to reconcile with their value of 93% obtained from the Li, Be and B abundances.

The nickel abundances in the cosmic rays and in the solar system is discussed in the view of explosive nucleosynthesis. There is no indication of different Ni/Fe ratios in the solar system and the cosmic rays and they both indicate a neutron excess of about 0.002.

A measurement of the isotopic composition of iron is presented in paper III. The study was made in collaboration with a group from the University of Kiel in West Germany. The detector is a combination of nuclear emulsion and cellulose nitrate plastics and the design goal for the experiment was to achieve adequate mass resolution for iron peak nuclei and to get a high rejection of particles interacting in the detector. When an ionizing particle penetrates a sheet of cellulose nitrate the material is chemically altered along the particle trajectory, which can be utilized to make the track visible by a suitable chemical etching. If the particle has a sufficiently high ionization the etching proceeds faster along the particle trajectory than on the bulk material. Cellulose nitrate is a good detector for ionization measurements since the etching

rate is a very steep function of the ionization. For a particle with a given charge and ionization the residual range is proportional to the mass of the particle. Thus the mass of a particle with a known charge can be determined by measuring ionization and residual range.

The detector was exposed in two balloon flights in order to increase the number of particles registered but due to geometrical restrictions only 17 iron nuclei remain in the final analysis. There is no straightforward way to make an absolute calibration of the mass scale and the results are interpreted on the assumption that the densest concentration in the mass distribution represents ^{56}Fe . Other possible assumptions do not seem to be consistent with the observed mass distribution. The isotopic composition observed in the detector is compared with a calculated distribution assuming solar system abundances at the source and an exponential path length distribution with a mean path length of 5 g cm^{-2} . There is no significant difference between the two isotope distributions, although the experimental errors are fairly large. Consequently this study does not support a large excess of ^{54}Fe or ^{58}Fe reported by some other investigators.

Reports on this experiment were given at

- 1) The 14th International Cosmic Ray Conference, Munich, West Germany, 1975.
- 2) The 9th International Conference on Solid State Nuclear Detectors, Munich, West Germany, 1976.
- 3) The 10th International Conference on Solid State Nuclear Detectors, Lyon, France, 1979.
- 4) The 16th International Cosmic Ray Conference, Kyoto, Japan, 1979.

Paper IV and V concern experimental technique developed in the preparations for an experiment in the neutrino beam at Fermilab in USA. The aim of the experiment was to study the decay of short-lived particles in nuclear emulsion and to measure their life-time. The set-up included a magnetic spectrometer for momentum measurements and an electromagnetic and a

hadronic calorimeter. A report on the neutrino experiment was given at:

Neutrino 79, International Conference on Neutrinos, weak Interaction and Cosmology, Bergen, Norway, 1979.

8 different groups took part in the collaboration: Bruxelles, Cornell, Fermilab, Lund, Oklahoma, Pittsburgh, Sidney and Toronto. Lund had the responsibility for the emulsion target which consisted of 15 liters of Kodak NTB-3 nuclear emulsion. Since the manufacturer does not deliver nuclear emulsion in pellicle form we had to pour the emulsion gel and make the pellicles ourselves. Tests showed that the commonly used methods for making thick pellicles did not work with NTB-3. As an example, NTB-3 emulsion dried on glass, stuck so hard to the glass that it was impossible to strip. Acrylic plastic worked better, but also with this material there were problems which had to be solved. This is treated in paper IV.

The reason for the choice of nuclear emulsion as a target and primary detector in the Fermilab experiment is the high spatial resolution, which is ultimately limited by the size of the silver halide grains (typically $0.2 - 0.3 \mu\text{m}$). For various reasons it is, however, difficult to visually detect short-lived particles which decay within about $10 \mu\text{m}$ from their production vertex. Paper V presents methods to measure and analyze such events in an objective manner. A technique was developed which permitted measurements of the coordinates of the center of a grain with a standard error of $0.02 \mu\text{m}$ and with negligible systematic errors. The coordinates of the grains of the tracks in an interaction are measured and they are used in a Chi-square test on the question: Do all the particles emerge from the same point in the emulsion? If the answer is negative a second decay vertex is looked for. The results must, however, be interpreted with some care since coulomb scattering and distortions in the emulsion might be involved. The technique has successfully been applied to some controversial events and our conclusions have, hopefully, settled the discussion of their interpretation.

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